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Analysis of Right-In, Right-Out Commercial Driveway Safety, Operations and Use of Channelization as Compliance Countermeasure

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ANALYSIS OF RIGHT-IN, RIGHT-OUT COMMERCIAL DRIVEWAY SAFETY, OPERATIONS AND USE OF CHANNELIZATION AS COMPLIANCE COUNTERMEASURE

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ABSTRACT

Access management and driveway design guidelines are critical in providing safe and controlled access to any land use adjacent to a highway. Two of the most common driveway types that provide viable access to land developments are full access and right-in, right-out (RIRO) driveways. Numerous studies in the past have shown that RIRO driveways are safer than full access driveways and can provide operational benefits. However, the effectiveness of a RIRO driveway is greatly dependent on driver compliance with turn restrictions. This research primarily focusses on the safety benefits of RIRO driveways and how these benefits can be compromised if drivers can make illegal movements into and out of RIRO driveways. A before and after case study quantifies the driver non-compliance to turn restrictions at a well-designed RIRO driveway, that meets the design criteria. The installation of longitudinal bollards resulted in immediate compliance improvements without negatively effecting driver patronage for the adjoining business.

A safety analysis of 3,774 driveways, including 268 RIRO driveways, along 6 major corridors in South Carolina provides evidence that crash rates for RIRO driveways without provision of a physically left turn prohibiting median treatment are higher than that of isolated RIRO driveways with beneficial treatments. A negative binomial model was developed using crash and driveway data from the 6 corridors and crash modification factors (CMFs) were developed for multiple cases which indicate that RIRO driveways with physical median treatment are safer than RIRO driveways without a physical median.

DEDICATION

I dedicate this thesis to my parents, Swarajya Lakshmi and Bhaskara Murthy Gorthy, whose kindness, unconditional love and humble ways have taught me the right approach in life and will always be a constant source of inspiration to me. I am truly thankful to them for their support and care in moulding me into what I am today.

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Even though care was taken to acknowledge all the personnel who helped me throughout this thesis, there could be a few contributions that are not mentioned. I would like to express my deepest gratitude to all whom I might have missed.

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CHAPTER ONE

INTRODUCTION

1.1. Introduction and Problem Statement

Commercial driveways are commonly found along various functional classes of highways, among which, major and minor arterials are significant in terms of volumes. The application of access management principles and driveway design guidelines is critical in providing a safe and controlled access to commercial driveways that are adjacent to highways. The most commonly used types of driveways in the United States are Full Access and Right-In, Right-Out only (RIRO). The intent of this research is to evaluate the access control treatments for RIRO commercial driveways and its adjacent streets. As per the National Cooperative Highway Research study on geometric design of driveways (1), left turn entry or exit movements comprise 70 percent of the observed driveway crashes. In the recent years, there has been a greater emphasis on the reduction of driveway crashes due to left-turning movements, though a variety of access management strategies, often placing turn restrictions at high-risk locations.

Use of raised median treatments along roadways is one of the most effective means to regulate driveway access, resulting in overall safety improvement through removal of left turning vehicles. This has been studied in the past through numerous research studies. Research by Florida DOT determined that making U-turn at a median opening along a bust multilane highway is 25% safer than a direct left turn from a side street or other access point (2). However, retrofitting raised medians along urban and suburban roadways with established commercial land use is often costly and raises concerns from businesses that depend on pass-by traffic (especially high turnover gas stations, convenient stores and fast-food restaurants). The business owners generally fear that added restrictions, due to access management treatments, will result in adverse consequences. These concerns include many misperceptions of business owners regarding economic indicators such as property values, gross sales, changes in available parking spaces or employees, and accessibility (3).

Along busy multilane highways, use of RIRO commercial driveways can provide viable access management treatments to address traffic safety and operational concerns. A RIRO driveway only permits vehicles to enter or exit through right turn maneuvers and is intended to eliminate left turn movements of vehicles to enhance safety. This is usually done through supplementing the driveway with a raised median island and separating the two directions of traffic flow along the road adjacent to the driveway using a raised median. At locations without raised medians, RIRO driveways may experience compliance issues with drivers making illegal left turns, even when raised channelizing islands are provided. Providing a raised median for highways may be difficult at several locations due to restriction for the roadways’ cross-sectional width, construction issues and raising concerns for business owners As the effectiveness of a RIRO driveway is greatly dependent on the driver compliance with turn restriction, this necessitates the use of alternate means to address compliance issues.

A RIRO driveway is usually supplemented with regulatory signs that preclude specific illegal left turn maneuvers. However, these signs are often ignored by drivers and a significant number of non-compliant movements are usually produced. The presence of a physical restraint may be required to ensure driver compliance and realize the safety benefits of a right-in, right-out only commercial driveway configurations, at the fullest potential.

1.2. Research Objectives

The focus of this research is to evaluate RIRO driveways with emphasis on design configuration, traffic volumes, regulatory compliance, and safety. Of particular concern is a comparison between RIRO driveways that have a physical median or barrier and RIRO driveways that do not. The hypothesis is that a lack of a physical median will result in driver noncompliance regardless of design which in turn compromises safety. The primary objective will be to quantify how safety is compromised. Other objectives will be:

- to quantify the compliance improvement attained through installing flexible delineators, by comparing the violations before and after the installation for a case study; and
- to study the impact of a physical longitudinal delineator on driveway volume by conducting a before and after case study at a commercial driveway

The major tasks for achieving the objectives will be to conduct: 1) a literature review of the safety effects of RIRO driveways and the use of longitudinal delineators; 2) a before and after case study of a commercial site location with added channelization safety countermeasures in the form of flexible travel lane delineators/bollards; and 3) a statistical safety analysis of driveways in South Carolina along selected corridors to quantify the the benefits of having physical barriers associated with RIRO driveways..

1.3. Benefits of this Research

It is anticipated that the findings of this research will lead to a better understanding of the safety benefits of alternative RIRO driveway configurations. Crash modification factors developed as part of the statistical analysis should be useful to decision makers responsible for choosing a RIRO driveway configuration.

1.4. Thesis Organisation

This thesis is organised into 7 chapters. Chapter 2 contains the survey of existing literature related to access management, safety and operational benefits of right-in, right-out driveways, raised medians, driveway geometric design specifications, and characteristics of longitudinal channelizing devices. Chapter 3 presents the before and after case study of a longitudinal bollard installation and summarizes driver non-compliance improvements after installation. Also, potential safety issues resulting from a well-designed RIRO driveway, without physical restriction are discussed in this chapter. Chapter 4 contains the analysis of 3,774 driveways, including 268 RIRO driveways along 6 major corridors in South Carolina. The chapter summarises the crash rates experienced by RIRO driveways with and without median treatments. Additionally, Chapter 4 includes a negative binomial regression model for various driveway attributes, including driveway type (RIRO with and without raised median and Full Access). The results of the analysis are summarised in Chapter 5, along with the crash modification factors for converting full access driveways to different classes of RIRO driveway (with and without raised median). Finally, the conclusions and recommendations for future research are concluded in Chapter 6.

CHAPTER TWO

LITERATURE REVIEW

The application of access management principles, to address safety issues and enhance traffic flow, has increased in the recent years. A significant amount of research has been done to emphasize the safety issues associated with a direct left turn (DLT) into and out of driveways along high volume roadways. The safety and mobility benefits of a Right Turn, U-Turn (RTUT) movements over DLTs have been studied in the past and results indicate that the crash rates are lower at driveways that restrict left turn movements. The literature review section summarises the previous research on access management and the median and driveway operational effects, alongside the design specifications, safety benefits and non-compliance issues of a right-in, right-out only driveway. The discussion also includes previous research on the use of longitudinal delineating devices and the studies conducted on driveways which have a RIRO supplemented by a full access driveway.

2.1. Access Management, Median and Driveway Operational Effects

In a research sponsored by Texas Department of Transportation, Eisele (4) conducted micro-simulation using VISSIM on three field test corridors and three theoretical corridors to investigate the operational impacts (travel time, speed and delay). The results indicated that on two of the three test corridors, replacing a Two Way Left Turn Lane (TWLTL) with a raised median resulted in an increase in travel time and a decrease in travel time on the other test corridor. Simulation results suggested small increases in travel times using raised median treatments compared to TWLTL conditions. In the same research, based on a detailed crash analysis on 11 test corridors, it was observed that crash rate increases with access point density, regardless of the median type. Also, a reduction in crash rate was found for all the test corridors which were investigated before and after installing a raised median.

Zhou (5) conducted field studies to quantify the operational impacts of replacing U-turns as alternatives to direct left turns (DLT) from driveways, at eight sites in Tampa and Clearwater areas of Florida. Delay and travel-time models were developed for DLT and right turn plus U-turn (RTUT), as a function of major and minor road traffic flow rates. In addition, operations models were used to measure system performance of a full median opening versus a directional median opening at a weighted-average total delay standpoint. The results indicated that U-turns have better operational performance than DLTs under certain traffic conditions, implying that directional median opening designs provide more efficient traffic flow compared to full median opening. The study also indicated that RTUT provides better safety in terms of traffic conflicts and fewer effects on through traffic of the major road.

In another study by Liu (6), the operational effects of using U-turns as an alternative to direct left turns (DLT) from driveways, were quantified along 34 roadway segments in central Florida. The delay and travel times of DLTs, right turn plus U-turn (RTUT) at median openings and RTUT at signalised intersections were compared, under different levels of driveway volume and major road through volume. The results indicated that the vehicles making a RTUT at a downstream median opening, before a signalised intersection, have comparable total travel times with the vehicles making DLTs at driveways. The study also concluded that the percentage of drivers selecting RTUT increases with the upstream through traffic, left turn volume from major road to driveway and total left turn demand at driveways.

The operational performance of DLT and right turn plus U-turn (RTUT) have been evaluated through simulation of a field study, conducted on six sites by Yang and Zhou (7). The traffic conditions under which replacing a DLT with RTUT would be beneficial from operational point of view, were studied using a combination of FRESIM and NETSIM. The delay and travel times were used as measures of effectiveness (MOE) at different levels of traffic volumes. Results indicated that, with an increase in the through traffic volume of the major road, the delay and travel time of direct left turns were higher than those of right turn plus U-turn.

In a research sponsored by Texas Department of Transportation, Qi (8) studied the design issues related to raised medians and alternative movements, namely restricted crossing U-turns (RCUTs), median U-turns (MUTs) and continuous flow intersections (CFIs). The results identified some critical design issues in application of raised medians. A set of implementation-oriented guidelines were developed focusing on applicability, geometric design, and access management of these three alternative movements, as follows:

- On roadways with narrow medians and high driveway densities, a median opening within the influence area (queue length) of a signalised intersection increases the safety issues related to the raised medians.
- Restricted crossing U-turn (RCUT) improved mainline traffic operation while compromising side street traffic operation.
- Substandard median turn lanes could result in significant total delays, is used consistently along a road.
- Converting full median opening into directional opening, reduced the crossing conflict points significantly.

Lu (9) conducted studies on evaluating the impacts of offset distance between driveways and the downstream U-turn locations (median opening or signalised intersection) on the safety and operational performance of vehicles making a RTUT movement. 4 different roadway conditions were considered, including 4-lane and 6-lane divided roadways with U-turns at median openings and at signalised intersections. Crash data, conflict analysis and operations analysis were used for field measurements from 68 sites, located in the Tampa Bay area in Florida. Additionally, crash history of 192 roadway segments was investigated. The results showed that crash rate and conflict rate at weaving sections decrease with an increase in the offset distance between driveways and the downstream U-turn locations.

The studies done in the past collectively support the implication that vehicles exiting driveways making a right turn, followed by a U-turn are relatively safer than vehicles making direct left turns movements. In addition, these studies have suggested that delay and travel time of indirect left turn movements (RTUT) is not significantly higher than a direct left turn movement, if a median opening is provided in advance of downstream intersections to facilitate U-turn movements. According to Highway Safety Manual (10), Two Way Left Turn Lanes (TWLTLs) should only be used at locations where the right of way limitations are present and channelization can be provided to constrain the drivers from making uncontrolled left turns.

2.2. Safety Benefits of Right-In, Right-Out (RIRO) Driveways

The studies conducted by Box (11) on 1350 driveways in three suburban communities of Chicago, Illinois, have determined that the left turn entry movement is responsible for one-half of the total driveway crashes. The proportion of accidents by movement have been summarised for each of right and left turning entry and exit movements. The study indicated that the total driveway crashed attributed to left turn entry vehicles account for 43 to 78 percent of the total driveway crashes and the left turn exiting vehicles accounted for 14 to 32 percent of total driveway crashes. The study also found a 57 percent reduction in driveway left turn entry accidents after installing a two way left turn lane (TWLTL) and suggested to either restrict or provide for left turn entry movements to the degree possible. For locations without a turn lane along the roadway for driveway traffic, this research indicated a 25 percent reduction in left turning vehicles at driveways when a TWLTL was provided.

Research by Stokes (12), which included 9000 driveways along 11 major corridors in South Carolina showed that converting full access driveways into right-in, right-out only driveways along the roadways, reduce the crashes by 55%. Other key finding indicates that the driveways within 150 feet of an intersection have nearly twice the crash frequency of driveways that are 150 feet to 300 feet from an intersection. From the driveways analysed in the research, it was concluded that the expected number of crashes for a full-access driveway are more than double that of a right-in, right-out driveway, for higher turnover land uses like fast-food restaurants and gas stations.

In a study to numerically analyse various driveway and median configurations, Dixon (13) used a risk assessment method to evaluate conflicts for various driveway configurations using a 55mph severe crash condition as a base comparison crash. A risk assessment index was developed though an expected gap analysis procedure using vehicle velocity, perception-reaction time, probability and volumes. The research findings indicate that the full access driveways (provided with a median opening) have nearly 10 times greater risk compared to that of right-in, right-out only driveways (provided with a controlled median).

Zhou studied the impact of cross-section related design elements on crash severity, crash type and the driver gap acceptance for turning maneuvers at urban arterial commercial driveway locations using data from corridor sites in Oregon, Arkansas and Oklahoma. Using crash data, traffic data and roadway information, supplemented by traffic interaction videos, the research conducted gap acceptance studies to determine critical gaps for driveways located along arterial roads. The results of the gap analysis indicated that driveway locations with raised medians experienced lower critical gap values than driveways with median openings. Additionally, a simulation analysis in CORSIM examined the influence of median type, traffic volume and access point density on traffic operational performance, which analysed 60 hypothetical driveways with aligned configuration. The simulation results suggested that the delay and travel times of corridors for raised median scenario is significantly lower than those of a two way left turn lane (TWLTL) for aligned driveway configuration and are close for staggered driveway configuration. Furthermore, the study implies that the removal of left-turning vehicles enables drivers to focus more directly on approaching vehicles from the left, resulting in beneficial shorter critical gap values for right-turn maneuvers exiting from driveways.

2.3. Safety Benefits of Raised Medians

All the driveways which are along a road with a continuous raised median are inherently RIRO driveways. Research in the past has indicated the fact that roadways with a raised median usually have lower crash rates compared to roadways with a two way left turn lane, other types of medians or without a raised median separating the opposing traffic flows. Gattis (15) studied the crash rates, travel times and other attributes of three urban street segments by comparing them, which have different levels of access control along them. All the three segments studied have roughly the same lengths, traffic conditions and similar commercial development lined along their sides. Additionally, all the three sections have four through lanes and relatively level grades. The relationship between crash rates and types of medians, categorized into roadways with no median, roadways with occasional left-turn lanes, roadways with two-way left turn lanes and roadways with raised or depressed medians, was developed. The study concluded that the raised or depressed medians generally had higher travel time but lower crash rates compared to the other two segments. The research also indicated that the better operational performance of the segment with raised median was not due to excessive speeds but due to elimination in causes of delay, such as major street vehicles slowing down for the vehicles turning off or into the through street from driveways.

In similar research, Mauga and Kaseko (16) have evaluated and quantified the impact of mainly two types of medians, namely raised medians and two-way left turn lanes, on traffic crashes in the midblock sections of roadways. Other access management attributes like traffic signal spacing, driveway density, median opening, and un-signalised crossroads were considered. The results showed that segments with a raised median had lowered the crash rate by 23% compared to segments with a two-way left turn lane. The higher densities of driveways and median opening resulted in higher crash rates and severity. For segments with raised medians, each additional median opening per mile resulted in 4.7% increase in the total crash rate.

2.4. Design Specifications of Channelizing Island of a RIRO Driveway

Among the various types of right-in, right-out only driveways, one of the most common type includes a raised island to channelize the traffic entering and exiting driveway and provides adequate signage and pavement markings. The following are some of the classes of RIRO driveways:

1. Painted Island

2. Raised Island
3. Painted Median (Double-Double Yellow)
4. Raised Median

NCHRP Report No. 659 states that driveway triangular islands (pork chops) are provided in the driveway entry throat at driveway intersection with the adjacent street. The purpose of a triangular island is to channelize right turns, discourage or prohibit left turn entry and exit movements and prohibit refugee for pedestrians. Figure 2.1 depicts three types of driveways which use triangular islands to discourage left-turn movements. A right-in, right-out only driveway discourages the left running movements both entering and exiting the driveway.

Examples of the geometric configurations of right in right our driveways that are followed in some states are as follows: Florida DOT does not use driveway triangular islands on undivided roadways. Lakewood, Colorado uses a 40 foot by 18-foot island (with an area of 360 sq. feet), where all the left turning movements are prohibited (1).

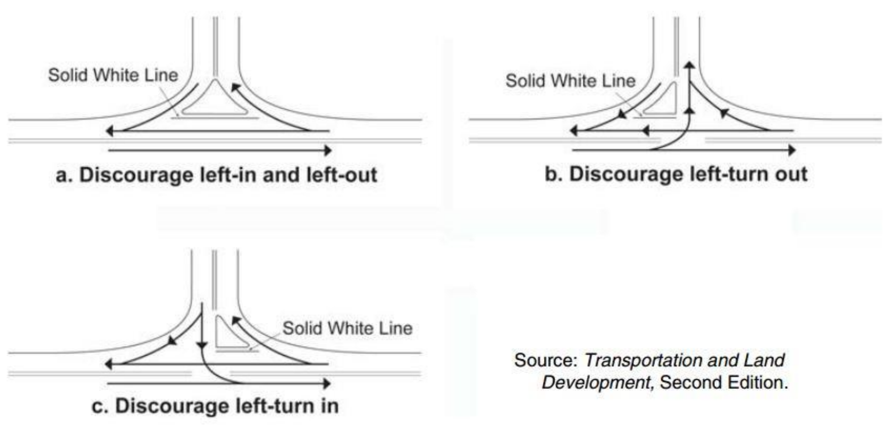

Figure 2.1: Types of turn restrictions similar to a RIRO

Different geometric configurations exist as the design guidelines for a triangular raised median island of a RIRO driveway. Some of the key design guidelines are provided by South Carolina Access and Roadside Management Standards (SC ARMS) and American Association of State Highway and Transportation Officials (AASHTO) Green Book titled, ‘A Policy on Geometric Design of Highways and Streets’.

2.4.1. Design Specifications of SC ARMS:

- Minimum Area of Concrete Island = 100 sq. feet (without pedestrian accommodation)
- Minimum length of each side after rounding for corners = 12 feet
- Minimum offset of the concrete island from the edge of the travel way = 4 feet (for a road with curb and gutter)

In addition, a typical RIRO driveway island has the following design features:

- A throat length of 40 feet from the edge of the travel way
- Minimum angle of intersection of driveway with the adjacent highway should be greater than 70 degrees
- A 24’’ solid white Stop Bar in the exit side of the driveway
- A throat width (driveway width) of 28 feet for a driveway with single lane for each of entering and exiting vehicles

2.4.2. Design Specifications of MUTCD:

- The vehicles exiting the driveway must be provided with a STOP sign followed by NO LEFT TURN sign consequently on edges of the triangular island

- The vehicles entering the driveway must be provided with a KEEP RIGHT sign on the edge at the beginning of the RIRO driveway
- The height of a roadside sign or sign on median should be a minimum of 7 feet for business, commercial or residential areas
- The minimum lateral offset provided for a roadside sign is 2 feet

2.4.3. Design Specifications of AASHTO:

- Minimum Area of Concrete Island = 100 sq. feet for urban areas (However, 100 sq. feet is preferred)
- Minimum length of each side of a triangular island = 12 foot (14 feet preferable)
- Most commonly used height of curb = 150 mm (6 inches)

While the guidelines provide the geometric features of an adequate island, the traffic engineer designing the driveway can adjust some features under proper authorisation. The island must be made sufficiently large to attract attention of the drivers and the curbed islands, leading into and out of driveways, are common in urban streets.

2.5. Bollards / Flexible Lane Delineators and Longitudinal Channelizers

In some cases, the raised island and the other physical features directing the drivers to make a right turn into and out of driveways are supplemented with a raised median along the roadway. In the presence of a raised median the drivers can make no illegal turns, given the median openings and signalised intersections are spaced at a significant distance from the driveway.

However, some of the RIRO driveways cannot have their adjacent major streets provided with a raised median, due to right-of-way issues. In such a case, there is a significant number of vehicles that make illegal movements entering and exiting the driveway, i.e., left-in and left-out. In such cases, longitudinal bollard / flexile lane delineators can be used to restrict the illegal left turn movements.

Flexible lane delineators/bollards and longitudinal channelizers are commonly used to guide the drivers horizontally and can be effective for speed-reduction or traffic calming (17). These devices when used in conjunction with other speed reducing devices, can reduce injury accidents by 25%. Flexible bollards are cost effective and can withstand vehicle impacts, however, placement needs should not impede with the normal functioning of the traffic. Figure 2.2 shows an example of the common types of flexible delineator posts, namely tubular markers. The flexible delineators are designed to withstand impacts from vehicles by transferring the stress from impact point to the base.

As per NCHRP Report 350, the length of the segment, excluding end anchorage devices should be at least three times the length of deformation predicted in impact, but not less than 30 meters for flexible barriers (such as a metal beam and post roadside barriers.

Figure 2.2: 3 Types of Tubular Markers (source: www.trafficwks.com)

The MUTCD specifications for tubular markers as follows:

- Shall have a minimum length of 450 mm (18 inches) and a width of 50 mm (2 inches) (Standard)
- Shall be made of a material that can be stuck without causing damage to the impacting vehicle (Guidance)
- Tubular markers shall be attached to the pavement to display the minimum width (2 inches) to the approaching road users (Standard)
- Tubular markers should only be used where space restrictions do not allow for the use of other more visible devices (Guidance)

Figure 2.3 depicts the MUTCD design specifications two types of tubular markers that are used for flexible longitudinal delineation.

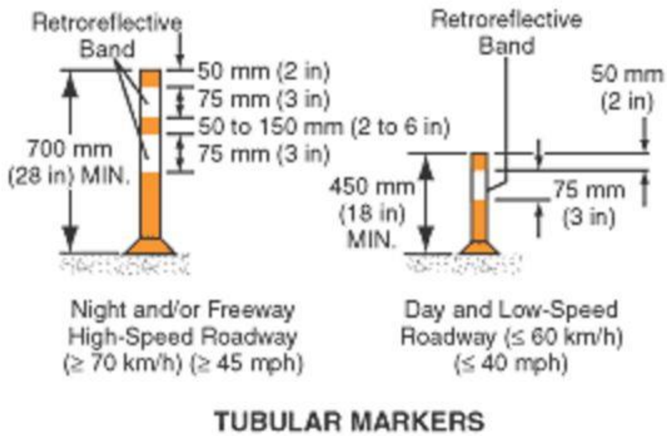

Figure 2.3: Design specifications of a Tubular Marker

Channelizers must not be used in excess to avoid the risk of loss in effectiveness as a speed-reducing device, as indicated in research by to Jurgita (17). In another study, Zhou has evaluated the safety and economic performance of two types of longitudinal channelizer's treatments. One of the treatments evaluates a conversion from full median opening to directional median opening and the other evaluates conversion from full median opening to left in only median opening. Results determined that the longitudinal channelizers can reduce the left-turn crashes by 60% and 45% for conversion to directional and left-turn in only median treatments, respectively.

The longitudinal bollards presented in this chapter, even though effective as delineation devices, can be damaged due to vehicle impact or wear out over time. Figure 2.4 shows a location with well-designed isolated RIRO driveway at New Spring Church, supplemented with longitudinal bollards on US 123 in Clemson, SC. It can be observed that the bollards are displaced from their actual position and the large gap thus formed allows the drivers to make left turn maneuvers without much difficulty. This can be seen in Figure 2.5. The images pertain to March 30, 2017.

Figure 2.4: Longitudinal Bollards at New Spring Church, Clemson, SC

Figure 2.5: Bollards displaced at New Spring Church, Clemson, SC

There are several other devices in the market that can provide longitudinal delineation at an isolated RIRO driveway like bollards. They could be more effective in terms of restricting the drivers from making left turn maneuvers at RIRO driveways. Some of the examples are interstate grade curb system, qwick kurb and road quick curb. An interstate grade curb system is depicted in Figure 2.6. An interstate grade curb system provides channelization on interstates, toll-ways and city streets and other functional classes of highways as lane separation devices.

Figure 2.6: FG 300 Interstate Grade Curb System

(Source: http://www.pexco.com)

Figure 2.7 depicts a qwick kurb system used as a channelization device and provides a raised curb system unlike the longitudinal bollards. Similarly, Figure 2.8 shows road quick curb used to channelize traffic with portable delineation devices.

Figure 2.7: Qwick Kurb System

(Source: http://www.qwickkurb.com)

Figure 2.8: Quick Curb System

(Source: www.alibaba.com)

2.6. Chapter Summary

The literature of a number of studies is in agreement that restricting left turn movements at driveways enhances safety and operational aspects of driveways. Most of the literature regarding restricting left-turn movements focuses on physical medians. Little discussion was found that mentioned non-compliance at RIRO driveways without median which is a focus of this thesis.

The chapter does provide driveway design guidelines and specifications in term of geometric design, signage and pavement markings that can be used to RIRO driveways. These guidelines will be used to determine if the case study driveways conforms to design standards.

The design and utility specifications of longitudinal bollards are presented alongside the issues associated with their usage in the field and an alternative longitudinal delineation device is presented that could be more effective in restricting the illegal movements at RIRO driveways.

CHAPTER THREE

METHODOLOGY AND ANALYSIS

PART I

The methodology for this research includes a two-phased approach as follows:

1. A before and after case study analysis of a fast food restaurant with an existing well designed Right-In, Right-Out only (RIRO) driveway experiencing a significant number of illegal left turn maneuvers, for which longitudinal channelizing devices were installed as a countermeasure
2. A safety analysis on 3774 driveways along 6 major highway corridors in South Carolina, using crash data from 2011 to 2014

In the current chapter the data collection and analysis of a before and after case study in Anderson, SC, US, is discussed and the driveway crash analysis of 6 major corridors in South Carolina is discussed in the following chapter.

Through the before and after case study, illegal turning movements have been quantified for each possible movement made by vehicles. Traffic volumes of the vehicles entering and exiting the primary driveway (RIRO) along a major state route, supplemented by a secondary driveway (FA) along a minor street, have been analysed as legally permitted and illegal movements. The percentage of left turning volume is depicted as a part of total volume, showing the significance of providing a physical median barrier to restrict the illegal movements of vehicles.

In the safety analysis, a collective driveway database of major highway corridors, including various driveway attributes such as driveway width, type, crash incidence from 2011 to 2014, etc., has been analysed to develop Crash Modification Factors (CMFs) associated with converting a full access driveway to a specific type of RIRO driveway. Thus, CMFs obtained from the negative binomial analysis shows the effect of having a physical median barrier on driveway access safety compared to full access and other isolated RIRO driveways without a physical longitudinal barrier.

3.1. Case Study Analysis at Fast Food restaurant in Anderson, SC

As a part of this research, a before and after case study was conducted initially to evaluate the effectiveness of longitudinal bollards in prohibiting illegal left turn movements. The case study primarily focused on quantifying the impact of bollards in reducing the number of left turning maneuvers. The study was performed at a Bojangles fast food restaurant located on South Carolina State Route 81 (SC 81) in Anderson, SC. The site includes a two lane RIRO driveway located on SC 81 and a two lane, full access driveway connecting with Financial Boulevard. Figure 3.1 shows the primary driveway (right-in, right-out only) and Figure 3.2 shows the secondary driveway (full access) as seen in the field.

Figure 3.1: RIRO Driveway connecting to SC State Route 81

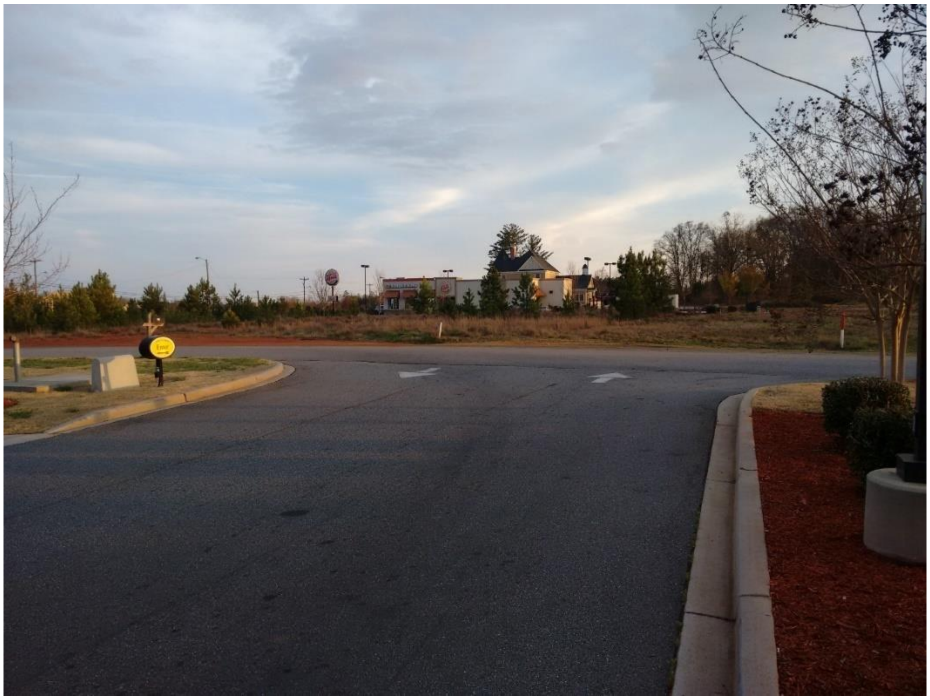

Figure 3.2: Full Access Driveway connecting to Financial Boulevard

The RIRO driveway includes a raised traffic island with signage and pavement markings intended to prevent left turning movements. However, through the initial visual observation and traffic volume data collected, illegal left turning vehicles entering and exiting the driveway have been evident and occurred with regularity.

The SCDOT classifies driveways based on the number of trips that will be generated by the land use. South Carolina Access Management Standards (ARMS) (20), provides information regarding the driveway classifications, including land uses that might be expected to generate the specified volumes as depicted in Table 3.1. With an hourly trip rate over 60 trips per hour and under 400 trips per hour, both the primary driveway (RIRO) and secondary driveway (Full Access) are classified as high volume driveways.

Table 3.1: SCDOT Driveway Classification based on number of trips generated

Driveway Classification	Expected trips	Example Land Use	Design Features
Low Volume	1 – 20 trips/day 1 – 5 trips/hour	Residential Drives (1-2 single family homes)	Typically designed with minimum requirements.
Medium Volume	21-600 trips/day 6-60 trips/hour	Small subdivisions with single family homes or apartments, small business or specialty shop	Typically designed with some higher volume features such as radial returns.
High Volume	601-4,000 trips/day 61-400 trips/hour	Convenience store, gas stations, or small shopping center	Typically designed with high volume features such as radial returns and turn lanes.

Major Volume	>4,000 trips/day >400 trips/hour	Large shopping center or regional mall	Designed with high volume features including radial returns, turn lanes and medians

Source: 2008 Access and Roadside Management Standards (SCDOT, 2008)

The geometric features of the Bojangles RIRO driveway exceeds specifications provided by Access and Roadside Management Standards (SC ARMS) (20), MUTCD and American Association of State Highway and Transportation Officials (AASHTO Green Book Chapter 9.7). The raised traffic island for the RIRO driveway is 118 sq.ft., exceeding the minimum required area of 100 sq.ft, as specified in ARMS. The driveway lane widths of 14 ft are also compliant with ARMS. The RIRO driveway is provided with four regulatory signs that are provided for traffic entering and exiting the driveway, as specified in ARMS. The signs provided include a NO LEFT TURN, KEEP RIGHT and a STOP sign. The use and placement of the ground mounted signs are provided in compliance with specifications in MUTCD (21). Even though the design of the isolated RIRO driveway meets design criteria specified in both ARMS and MUTCD, illegal movements are still a chronic issue causing potential safety issues. Some of the other design specifications that are satisfied by the existing driveway geometry are summarised in Table 3.2. An AutoCAD drawing depicting the site location with respect to the existing roadway geometry and pavement markings is depicted in Figure 3.3.

Table 3.2: Driveway Design Specifications Satisfied by the RIRO

Design Guideline Description	Specification	Provided
Area of Concrete Island (ARMS)	Min. 100 sq. ft	128 sq. ft
Length of each side of Island (ARMS)	Min. 12ft	16’×16’×16’
Offset of the island from edge of the travel way (ARMS)	Min. 4ft	6 ft.
Solid white Stop Bar Width (MUTCD)	12 in. to 24 in.	24 in.
Driveway width (Throat Width)	Min. 28ft	24 ft.
Height of the sign	5ft in rural areas	5 ft.
Lateral offset provided for the sign	Min. 2ft	2 ft.
Lane Width	14ft	14 ft.
Angle of intersection of driveway with the adjacent highway (ARMS)	Min. 70 degrees	90 degrees
Width of dividing pavement marking	4 in. to 6 in.	4 in.
Driveway Length (Throat length)	Min. 40 ft	56 ft

FIGURE 3.3: Case study site schematic

The Annual Average Daily Traffic (AADT) data was obtained from the South Carolina Department of Transportation (SCDOT) website for the years 2010 to 2015. Figure 3.4 depicts a Google Earth Map of major state routes near the case study location. SC State Route 81 is adjacent to the RIRO Driveway and has an AADT of 13,600 vehicles per day in 2015 and an average AADT (2010 to 2015) of 13,150 vehicles per day and SC State Route 839, which is near the location has an AADT of 13,600 vehicles per day in 2015 and an average AADT (2010 to 2015) of 9,350 vehicles per day. The major highways (SC 81 and SC 839) and the study location is depicted in Figure 3.4.

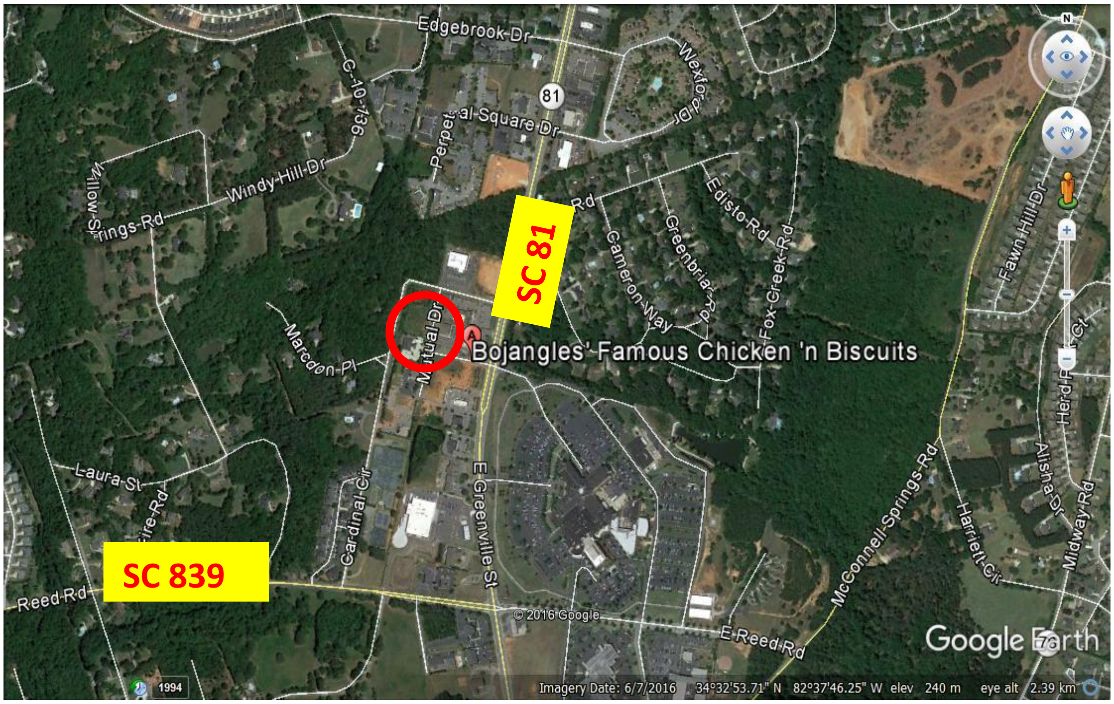

FIGURE 3.4: Case study site location and major highways in the vicinity

3.2. Driveway Volume Data Collection

Vehicle counts entering and exiting the site were collected initially on Tuesday, June 21, 2016 before the bollards were installed. The data was collected in a video format using pole mounted video cameras positioned to record traffic movements for both of the driveways of the site. Video data collected was analysed visually and the traffic counts of the driveways including the occurrence of illegal maneuvers were recorded for both AM and lunchtime peak hours during the following times:

AM Peak Period: 7 AM – 8:30 AM

Lunchtime Peak Period: 11:30 AM – 1 PM

The peak hours were chosen because they represent the busiest hours of a typical Bojangles during a day. The data collection was done during a Tuesday and a Thursday because Tuesdays, Wednesdays, and Thursdays typically show similar traffic characteristics. Figure 3.5 depicts the data collection days for the before bollard installation, along with potential bollard installation dates and the 3 data collection days after installing bollards. The before installation data was collected on June 21st, 2016 (Tuesday) and after installation data collection was done on July 14th, 2016 (followed by two consecutive Tuesdays (July 19th, 2016 and July 26th, 2016). The bollards were installed in the field on either July 12th, 2016 (Tuesday) or July 13th, 2016 (Wednesday).

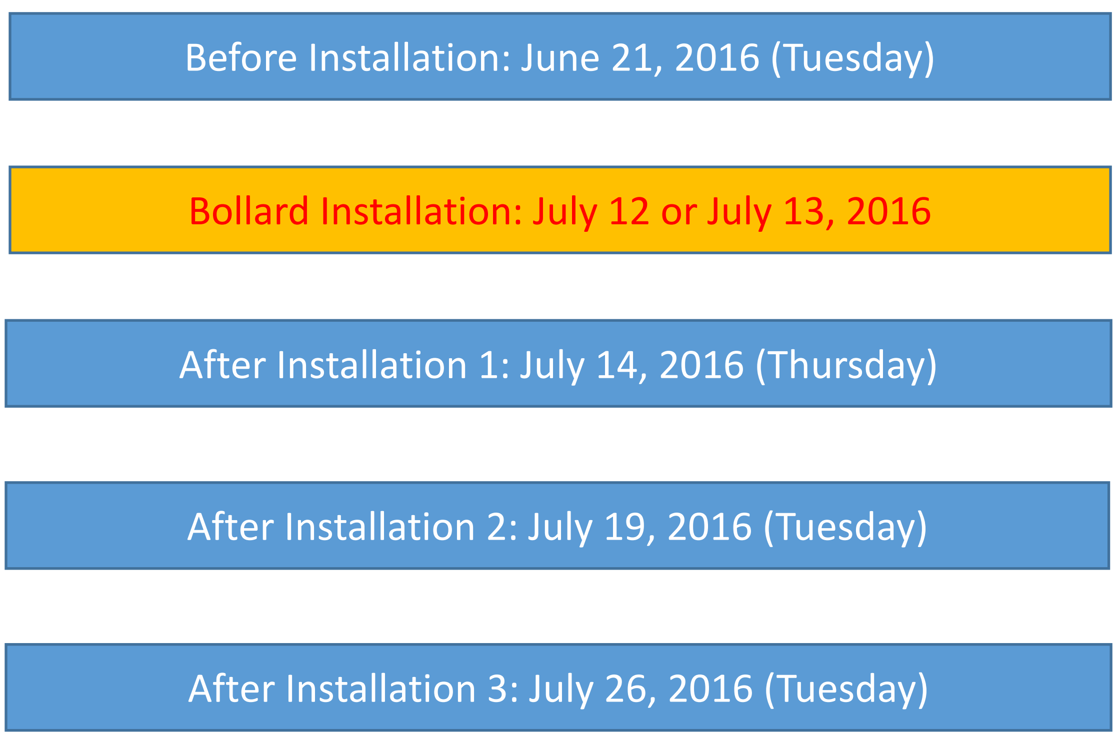

FIGURE 3.5: Bollard Installation and Analysis Period

3.3. Data Collection System

Driveway data was collected initially in video format so that driver behaviour could be monitored in addition to recording the movements. The video data provided adequate clarity and coverage to observe driver behaviours such as vehicles trying to exit the driveway through a left turn maneuver but gave up due to heavy through traffic on the adjacent highway (State Route 81).

A low-cost traffic data collection system was used for collecting the video data. The video from this system was processed manually using JAMAR digital count boards. The key components of the system are the generic all-weather action camera (ANART) and the mounting system. The camera system is a light weight, portable, and environmentally protected setup with sufficient memory and power supply to last for a minimum of 1 1/2 hours (the analysis period for this study is 90 minutes). The camera is enabled with Wi-fi to allow viewing during data collection. This ensured adequate coverage of the driveways. The basic setup for the data collection system at a driveway includes the camera enclosed in a protective case, a telescoping pole, a mounting bracket, battery supply, and memory. Figure 3.6 shows the camera enclosed in a protective case. This camera is mounted on the telescoping pole using the mounting bracket and raised and attached to an existing utility or light pole in the field. The setup is shown in Figure 3.7 and a video image is shown in Figure 3.8. The complete installation usually takes about 5-10 minutes in the field.

Figure 3.6: Camera Setup

Figure 3.7: Data Collection System

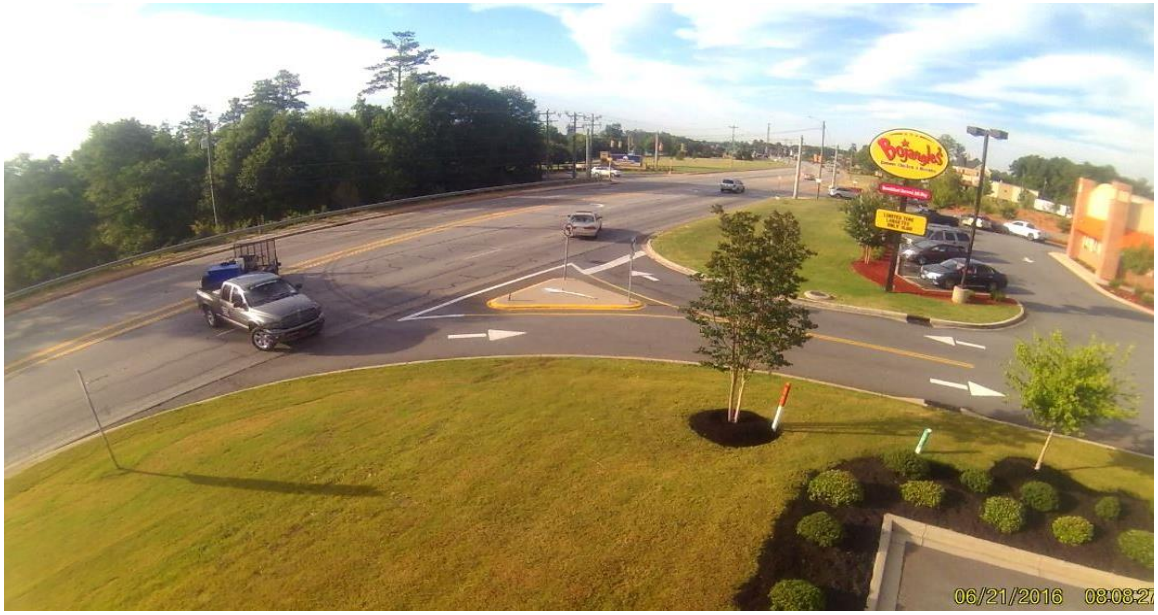

Figure 3.8: Coverage of Video Data from the ANART cameras

3.4. Driveway Data Analysis at Bojangles Fast Food Restaurant

The traffic counts extracted from the videos include the number of vehicles making each of the possible movements into and out of the driveways. The 4 major movements are: right turn entry, right turn exit, left turn entry and left turn exit. All possible movements are possible at the full-access Financial Blvd. driveway while only right turn movements are legally permitted at the RIRO driveway on Highway 81. Figure 3.9 shows a typical right turn entry maneuver at the RIRO driveway and Figure 3.10 shows a typical right turn exit maneuver at this driveway before bollard installation. An illegal left-turn entry movement into the driveway is depicted in Figure 3.11 and a left-turn exit movement is depicted in Figure 3.12 before bollard installation. Illegal left turn maneauvers before the bollard installation was found to be significant, despite the driveway meeting all design critera.

Figure 3.9: Typical Right Turn Entry Movement

Figure 3.10: Typical Right Turn Exit Movement

Figure 3.11: Typical Left Turn Entry Movement

Figure 3.12: Typical Left Turn Exit Movement

Before Bollard Installation

The videos were analysed and the turning movement data including illegal maneuvers was tabulated. The counts were summarised for traffic entering and exiting the RIRO only driveway for the AM and lunchtime peak periods. Illegal turning maneuvers made by the drivers before bollard installation ranged from 11-15 percent of total driveway volume during the two peak periods (morning and lunchtime) collected.

A closer look at driver behaviour from the video and field observation during the data collection periods indicated that there would have been several more illegal turning maneuvers however these vehicles gave up because of the heavy conflicting volume “peer pressure” by following drivers. The heavy through traffic on SC 81 made it difficult for drivers to find adequate gaps to make illegal left turn maeuvers. It was observed that multiple drivers waited at the STOP bar to make a left turn out of driveway and finally made a right turn. This suggests the possibility that the percentage of driver making illegal movements would be higher during non-peak traffic on SC 81.

Bollard Installation

The flexible delineating bollards were installed at the site on July 12th, 2016 or July 13th, 2016 to discourage illegal left turning movements into and out of the RIRO driveway. The offsets of the bollard segment relative to the driveway are depicted in Figure 3.13 where the green line segment represents bollard segment.

Bollards were installed with the following geometric features:

1. Distance between 2 delineating posts (bollards) = 4.75 feet

2. Number of delineating posts (bollards) = 30

3. Total length of bollard segment = 138 feet

4. Offset of bollard segment from center of the driveway (left) = 74 feet

5. Offset of bollard segment from center of the driveway (right) = 62 feet

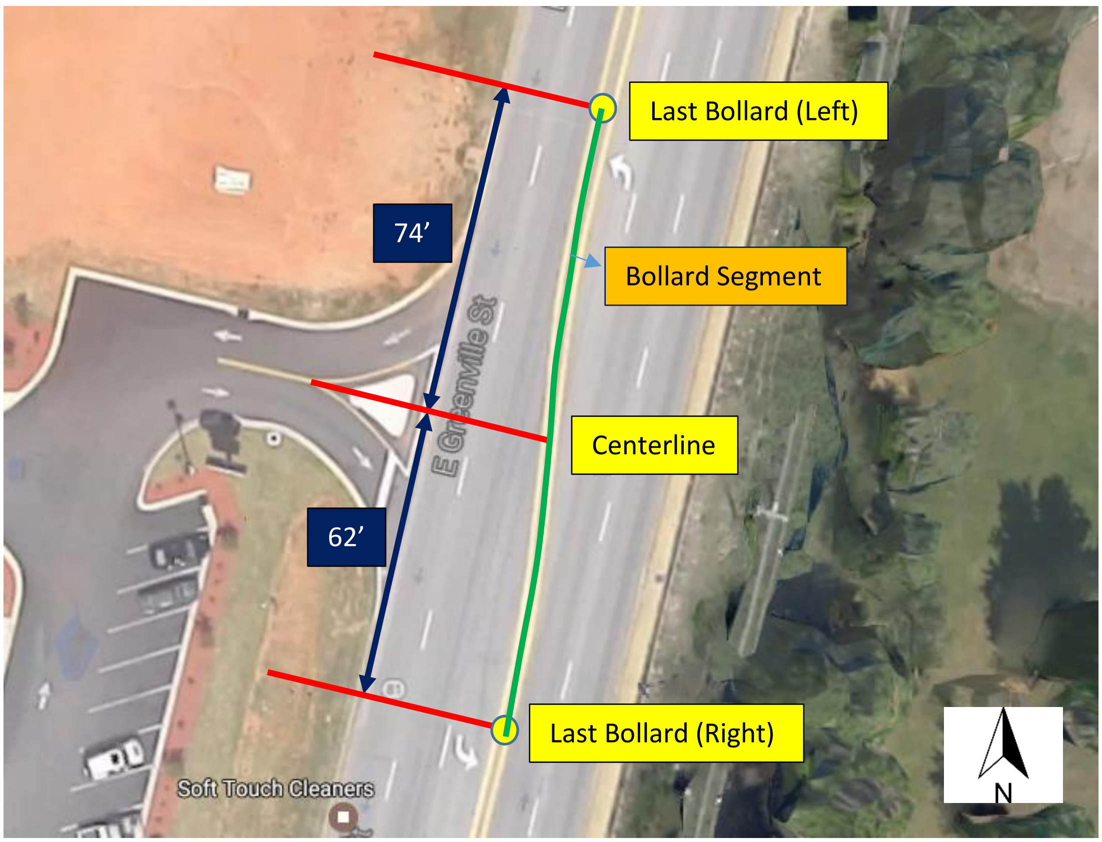

Figure 3.13: Bollard segment relative to driveway

The following are the cost details of Delineator Posts at Bojangles on SC 81 in Anderson:

Material Costs:

- Delineators = 30 ($36.95 per each) + $60 (freight) = $1,246.01

- Adhesive = Liquid nails construction adhesive = Approx. $50

Labor Costs:

- SCDOT Crew cost = Approx. $255 (3 hrs. of labor)
- Traffic Control = variable (a contractor would likely charge $250 - $ 1,000 for traffic control in a median, but varies with location)

Total cost = Approx. $2,000

The cost of Qwick Kurb for the same segment is estimated to be over $10,000, which is significantly greater than that of longitudinal delineator posts.

After Bollard Installation:

While the volumes indicate that the bollards were effective in reducing illegal left-turns at the RIRO driveway, these maneuvers were not eliminated completely. Some drivers drove the wrong way along SC 81 just after the intersection to bypass the bollards and enter the driveway. Other illegal movements made by drivers include making U-turns across a double-double yellow line (painted median) just beyond the location of the bollards, to access the RIRO driveway. Similarly, some of the drivers exiting the driveway initially made a right turn followed by a U-turn just after the bollards instead of going all the way to the intersection. Figure 3.14 shows the RIRO driveway after bollard installation.

Figure 3.14: RIRO with bollards installed

It is also worth noting that the longitudinal delineating bollards, while effective in working as channelization devices, are prone to be knocked off. Figure 3.15 shows that some of the bollards towards the right end were knocked off at the driveway as of March 24^{th}, 2017.

Figure 3.15: RIRO Bollards as on March 24, 2017

3.5. Driveway Data Summary

Table 3.3 and Table 3.4 summarize the traffic counts for vehicles turning into and out of the right-in, right-out only driveway for the AM and lunchtime peak periods. Table 3.5 summarizes traffic counts for entering and exiting the secondary full access driveway connecting to Financial Boulevard for both the AM and lunchtime peak periods. By combining volumes for both driveways, total site traffic can be determined during each period (1 for before period and 3 for after periods), which is given in the last row of Table 3.5.

TABLE 3.3 Morning/AM (7:00 am - 8:30 am), RIRO Driveway Traffic Counts

Turning movement	Legally Permitted?	Morning Peak Volume			
		Before[a]	After[b]	After[c]	After[d]
Right In	Yes	69	65	62	54
Right Out	Yes	37	67	58	61
Left In	No	12	4	3	0
Left Out	No	7	1	1	0
In-bound vehicles		81	69	65	54
In-bound non-compliance (%)		14.8%	5.8%	4.6%	0%
Out-bound vehicles		44	68	59	61
Out-bound non-compliance (%)		15.9%	1.5%	1.7%	0%
Driveway Volume		125	137	124	115
Overall non-compliance (%)		15.2%	3.6%	3.2%	0%

TABLE 3.4 Afternoon (11:30 am - 1:00 pm), RIRO Driveway Traffic Counts

Turning movement	Legally Permitted?	Afternoon Peak Volume (Lunchtime)			
		Before[a]	After[b]	After[c]	After[d]
Right In	Yes	31	44	24	33
Right Out	Yes	39	49	31	49
Left In	No	8	2	3	0
Left Out	No	1	0	0	2

In-bound vehicles	39	46	27	33
In-bound non-compliance (%)	20.5%	4.3%	11.1%	0%
Out-bound vehicles	40	49	31	51
Out-bound non-compliance (%)	2.5%	0%	0%	3.8%
Driveway Volume	79	95	58	84
Overall non-compliance (%)	11.4%	2.1%	5.2%	2.4%

TABLE 3.5 AM and Afternoon FA Driveway Traffic Counts & Total Site Traffic

Turning movement	**Morning Peak Volume**				**Afternoon Peak Volume**			
	Before[a]	**After[b]**	**After[c]**	**After[d]**	**Before[a]**	**After[b]**	**After[c]**	**After[d]**
Full Access In-bound	52	76	53	71	49	49	47	55
Full Access Out-bound	43	55	48	48	50	46	35	33
Total Full Access Driveway	95	131	101	119	99	95	82	88
Total RIRO Driveway	125	137	124	115	79	95	58	84
Total site traffic	220	268	225	234	178	190	140	172

[a] data collected on Tuesday, June 21, 2016
b data collected on Tuesday, July 14, 2016
c data collected on Tuesday, July 19, 2016
d data collected on Tuesday, July 26, 2016

Even though there was one dataset for before bollard installation and three datasets for after installation, total site traffic remained reasonably consistent for the fast food restaurant. The first after date exhibited the highest site traffic for both the morning and lunchtime peak periods, however this may have occurred due to data collection on a different day of the week (Thursday). All other data collection dates were Tuesdays. The initial indication from the before and after study is that: bollard installation has improved driver compliance with turn restrictions and exhibited no adverse impacts on business patronage.

CHAPTER FOUR

METHODOLOGY AND ANALYSIS

PART II

4.1. Corridor Crash Inventory

A large amount of data was evaluated for accuracy in South Carolina, which includes crash data, roadway characteristics, and driveway characteristics. At the initial stages, 30 corridors within the state with a high incidence of driveway related crashes in the state were identified for further analysis. The driveway related crashes are coded as junction type 02 in the crash database. The top 30 corridors were identified based on a 3-year combined average crash frequency ranking.

Based on further analysis a set of 11 corridors with the high crash incidence as well as spatial distribution throughout the state were selected (Figure 4.1). Table 4.1 depicts the name of the route, length of analysis segment, crash incident along the segment and 3-year average crash rank of driveway (from 2010, 2011 and 2012). To minimize high crash frequency bias, the selected corridors were all greater than 10 miles in length with sections that varied considerably in many regards including driveway density, corner clearance, median type, AADT, crash frequency, etc.

However, among these 11 corridors some were in Cities where much of the crash reporting is done by city police who are not equipped with the SCCATS crash reporting system. The precision of the crashes geocoded using SCCATS is much better than the handheld GPS reporting systems which is what Charleston uses. To ensure crash geocoding accuracy, a total of 6 corridors were identified and used in the analysis. These will be identified in the next section.

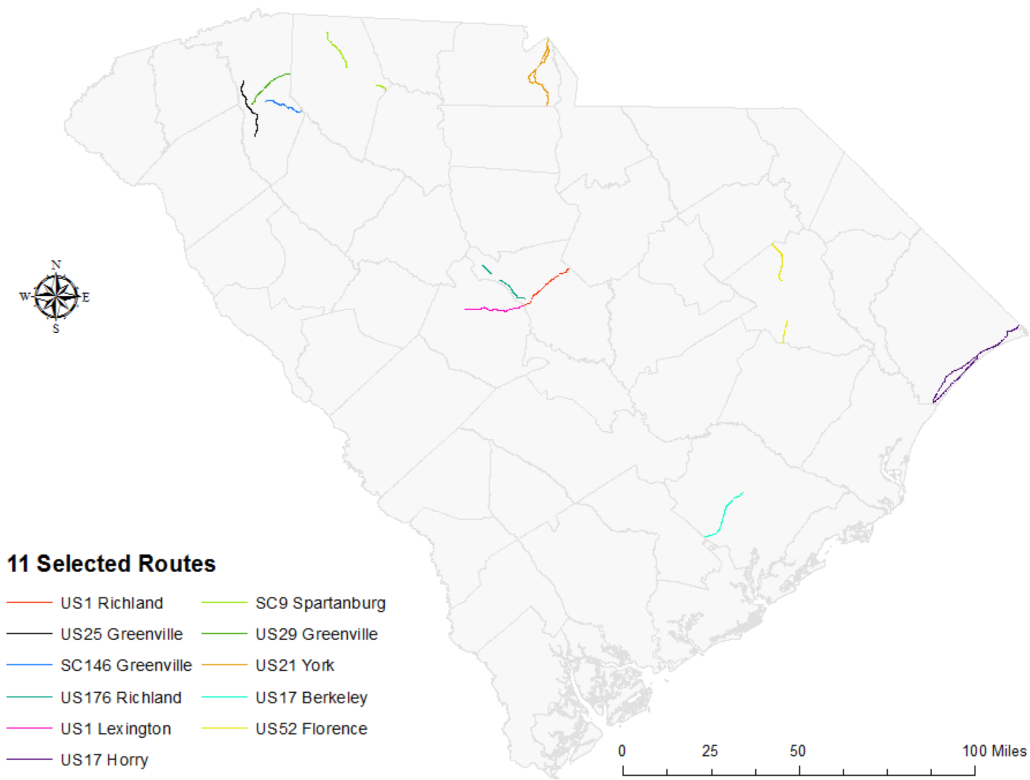

Figure 4.1: Map of 11 corridors

Table 4.1 Ranking of 11 Corridors *(Source: Sarasua et.al., Support for the Development and Implementation of an Access Management Program through Research and Analysis of Collision Data, South Carolina Department of Transportation, 2015)*

COUNTY	ROUTE TYPE	ROUTE NUMBER	LENGTH (MILES)	3 YEAR DRIVEWAY AVG RANK	DRIVEWAY CRASHES
Richland	US	1	18.5	1	353
Greenville	US	25	18.7	2	309
Greenville	SC	146	13.5	3	294
Richland	US	176	15.8	4	274
Lexington	US	1	17.6	5	214
Horry	US	17	55.4	6	195
Spartanburg	SC	9	15.8	7	173
Greenville	US	29	15.4	8	159
York	US	21	35.6	9	147
Berkeley	US	17	18.8	11	149
Florence	US	52	20.4	12	131

4.2. Corridors for Crash Summary Analysis

The safety analysis of RIRO driveways focused on crashes along 6 corridors in South Carolina occurring from 2011 to 2014. A driveway database for the selected corridors was created in a Geographic Information System (GIS) and included driveway information such as whether a driveway is a RIRO and if a median was present. RIRO driveways were further classified based on geometry and signage. The classification of RIRO fall under the following categories: painted island, raised island, and signage presence. The RIRO driveway attributes also include the condition of RIRO channelization treatment. Driveways were identified and populated with attribute data by analysing Bing and Google digital maps and Google Streetview images.

Initially, data was tabulated for more than 9,000 driveways, including 1,365 RIRO driveways along 11 corridors in South Carolina. For the 6 selected corridogs, there were, 3,774 driveways including 268 RIRO driveways. The following are the 6 corridors analysed for the driveway crash analysis:

1. SC 146 – Greenville, SC
2. SC 9 - Spartanburg, SC
3. US 1 - Richland, SC
4. US 17 - Berkeley, SC
5. US 176 - Richland, SC
6. US 25 - Greenville, SC

4.3. Development of RIRO Driveway Crash Rates

To determine the safety effects of right-in, right-out only driveways on crash incidence on the roadway, it is necessary to associate driveway crashes with driveways. Using queries to select possible crash types that could be associated with driveways (such as rear end, angle, etc.), the assumption was that any crashes within an influence area of a driveway are considered driveway related crashes for that specific driveway (23).

Driveway Attribute Data

The SCDOT Roadside Inventory Management Systems (RIMS) road characteristics database is used for the driveway attribute data collection. Based on aerial imagery (Bing and Google street view), driveway attribute data has been populated for the selected 6 corridors. The categories and description of attribute data populated for the 3,774 driveways, including 268 RIRO driveways are summarized. Figure 4.2 depicts the driveway attributes for a full access driveway located at a high turnover land use. Input codes were provided for each driveway attribute with multiple categories, starting from 1. Driveways which do not fall under any specific category for a driveway attribute will by default be populated with an input code 0. The driveway attributes used for the analysis fall under "Full Access" and 'Right In-Right Out Class'. The RIRO attribute is further stratified into input codes from 1 to 9, representing various types of RIRO driveways. A full access driveway is given an input code 0 for this category.

Driveway Buffer Creation

To effectively identify driveway related crashes, it is crucial that the driveway influence areas are as precise as possible. One possible approach is to buffer an area on the travelway adjacent to each driveway to delineate the influence area. This can be done using ArcGIS buffer techniques. For this purpose, roadway centerline segments are needed along with information related to the roadway width.

FID	3484	D_Type	3
FID_1	3484	Aux_Lane_R	1
Join_Count	1	Med_Type	4
TARGET_FID	7	Parking_Ty	1
POINT_X	0	D_Use	2
POINT_Y	0	D_Class	4
NEAR_X	0	D_Use_Size	4
NEAR_Y	0	Sh_Use	2
Id	0	No_D_Use	1
Segment_No	0	D_Hierarch	3
Driveway_N	13	D_Control	1
Seg_Dr_No	0	D_Control_Binary	0
D_Spacing	542	DWidth_P15	34
D_Radius	20	Shape_Leng	63.12232808
D_Width	39	BUFF_DIST	34
N_Entry_Ln	1	Corridor	SC146Greenville
N_Exit_Ln	1	Student	Xi
D_Angle	1	Check	0
D_Corner_C	0	AADT	12100
D_Throat	45	SpeedLimit	45
Sight_Dist	1	FAorRIRO	FullAccess

Figure 4.2: A FA Driveway (Top) and Attributes Associated (Bottom)

SCDOT maintains a GIS layer of roadway centerlines for all roads on the South Carolina state route system. Attribute data for centerline segments is either associated with its entire segment or linearly referenced by mile point using dynamic segmentation. Using the buffer by attribute feature in ArcGIS allows creation of a polygon based on an attribute of individual segments. By using this feature and offsetting from centerline segments by half of the roadway width RIMS attribute across both sides of the line, travelway buffers were created for all 6 corridors.

Figure 4.3 shows the travelway buffer for a section of SC 146 along Greenville, SC., which includes the centerline along with driveway points and crash locations (for 2012) depicted as point shape files in ArcGIS. Additionally, the legend depicts the names of the layers used for the travelway buffer creation in ArcGIS.

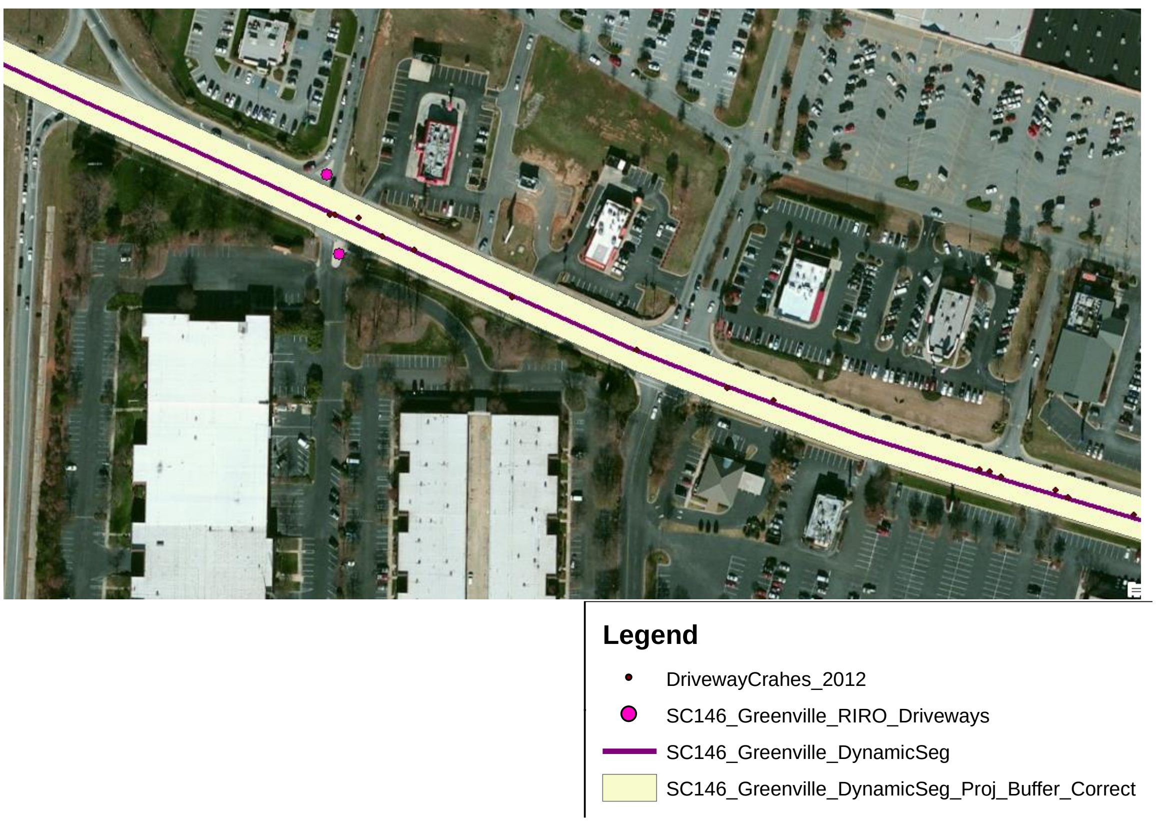

Figure 4.3: Travelway Buffer

The travelway buffers created using the roadway centerline initially did not cover the entire pavement width at some locations as seen in Figure 4.4. The top left image in Figure 4.4 depicts a travel way buffer being offset from the pavement area because the centerline segment doesn't represent the actual centerline of the paved roadway as seen in aerial imagery. The top right image shows the corrected buffer. The bottom image shows a roadway segment where the RIMS data travelway width was not correct resulting in a travelway buffer that did not represent the actual travelway at the location. The bottom right image shows the corrected buffer.

US 1 Richland, centerline offset problem

US 1 Richland, centerline offset correction

US 1 Richland, travelway width problem

US 1 Richland, travelway buffer correction

Figure 4.4: Travelway Buffer Correction

Upon creating the travelway buffers, driveway buffers were created, to represent their influence area from a crash standpoint. One problem with standard circular buffering based on location of the driveway access point is that it would bias toward crashes that occur closer to the edge of the road (near the driveway entrance). Ideally, rectangular buffers would provide a better indicator of a driveway's influence area. Thus, a model was created that could make rectangular buffers that stretched across the roadway as shown in Figure 4.5.

Two models were created depending on driveway type: a model for full access driveways that creates buffers extending across all travel lanes; and a model for right-in right-out (RIRO) driveways that creates buffers that extend to the roadway centerline.

Figure 4.5: Full-access and RIRO driveway buffers

Additionally, driveway buffers were created for RIRO driveways that extend across all travel lanes similar to full access driveways. The reason for this more conservative approach is because our initial assumption that the crashes geocoded by the police officers completing the crash report are pinpointed to their precise locations is not true. Instead, they geocode crashes close to the centerline shown on their GIS map display. The reason for this is that centerlines provide the only spatial reference to the officer. Edge of pavement lines or underlying images are not provided. As our centerline has been modified and does not necessarily align exactly with the centerline used by the police, there is a possibility of having one of the following three scenarios at driveway buffers, using half buffer overlays (as depicted in Figure 4.6):

Scenario 1: Centerline used by police and centreline used in our research align exactly (Crashes are counted accurately assuming the officer locates crashes on the correct side of the road relative to the centerline)

Scenario 2: Centerline used by police is away from and centerline used in our research but farther off from the half buffer (Possibility of undercounting crashes)

Scenario 3: Centerline used by police is away from and centreline used in our research but inside the half buffer (Possibility of overcounting crashes)

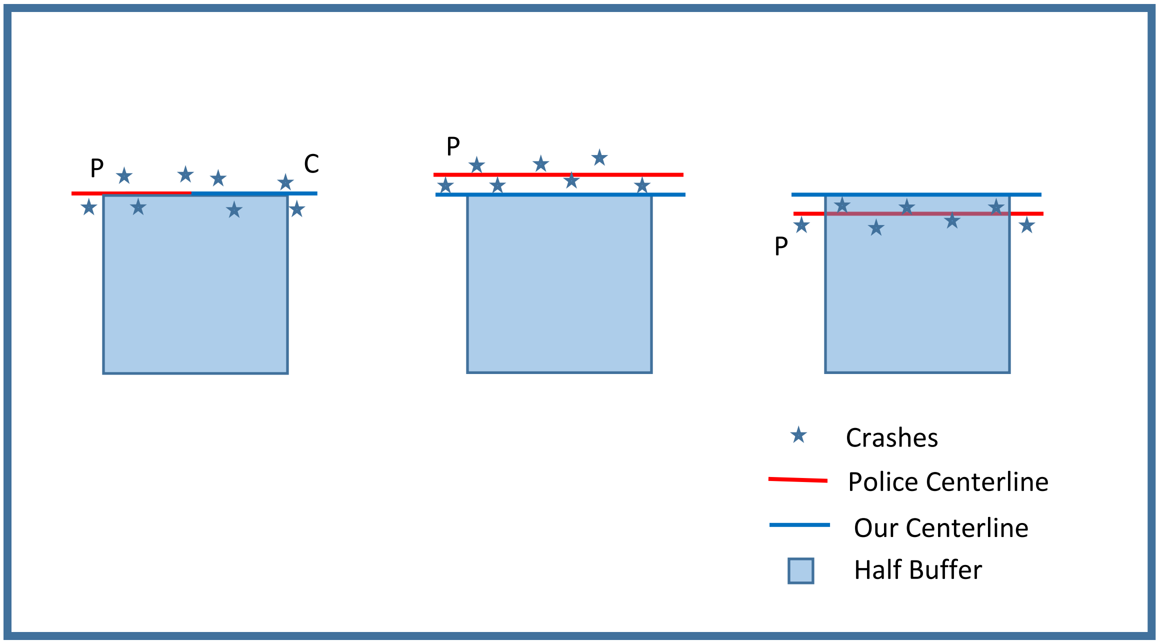

Figure 4.6: Three Scenarios Possible with Half Buffer Overlay

A comparative summary analysis was done for RIRO driveway buffers extending across all the travel lanes and RIRO buffers extending to the roadway centerline. The crash data from 2011 to 2014 were aggregated and used for this analysis.

Driveway width attributes from the driveway database are used in both the models (full access and RIRO) to create the driveway buffers. The driveway buffer width is the driveway width plus thirty feet to accommodate about a car length on each side of the driveway. The 30-foot value was identified in a separate analysis using different values starting at 0 (thus the driveway influence area would only be equal to the actual driveway width) to 60’ in 6-foot increments. The number of crashes that fell within each buffer was determined and graphed. An inflection (abrupt change in slope) occurred for 30-feet.

4.4. RIRO Driveway Crash Summary

Once the driveway buffers were created for the selected 6 corridors, potential driveway crashes from 2011-2014 were aggregated in each RIRO driveway buffer using the GIS overlay tool. The resulting crash counts aggregated in each buffer are used to calculate the 4-year crash rate for each driveway. The average 4-year crash rate of the 6 corridors represents the total number of crashes that fell within driveway buffers divided by the total number of driveways.

The crash rates of RIRO driveways along various corridors were developed for RIRO buffers with two approaches:

1. FA buffers extending across all the travel lanes and RIRO buffers extending until roadway centreline (RIRO Half Buffer)
2. Both FA and RIRO buffers extending across all the travel lanes (Both Full Buffer)

Figure 4.7 shows driveway crash rates by year for all the years between 2011 and 2014 for full and half buffers of RIRO driveways. Figure 4.8 shows the same depiction for the crash rates by year between 2011 and 2014, after the overlapped crashes have been removed for the RIRO driveways which are opposite to each other. The removal of overlapping crashes for Full Buffer RIRO driveways was done to reduce over-counting of the crashes for these driveways. Crashes overlapping between two RIRO driveways which are on opposite directions were assigned to one of the driveways for crash summary analysis.

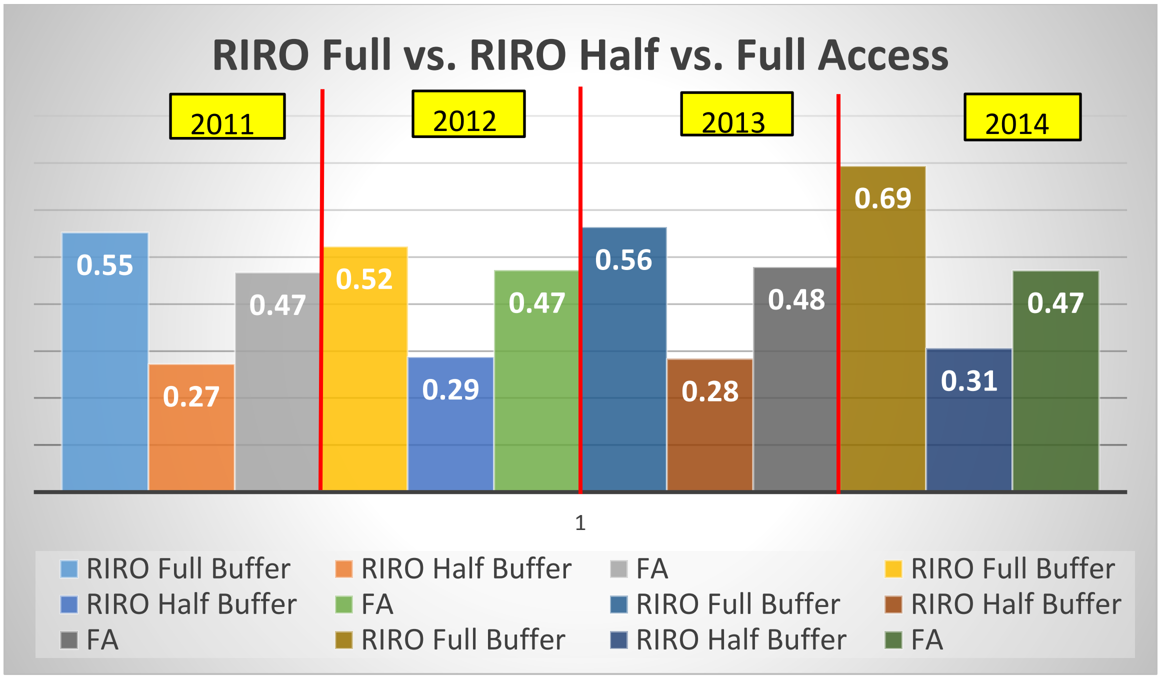

Figure 4.7: Crash Rates by Year for Driveways (2011 - 2014)

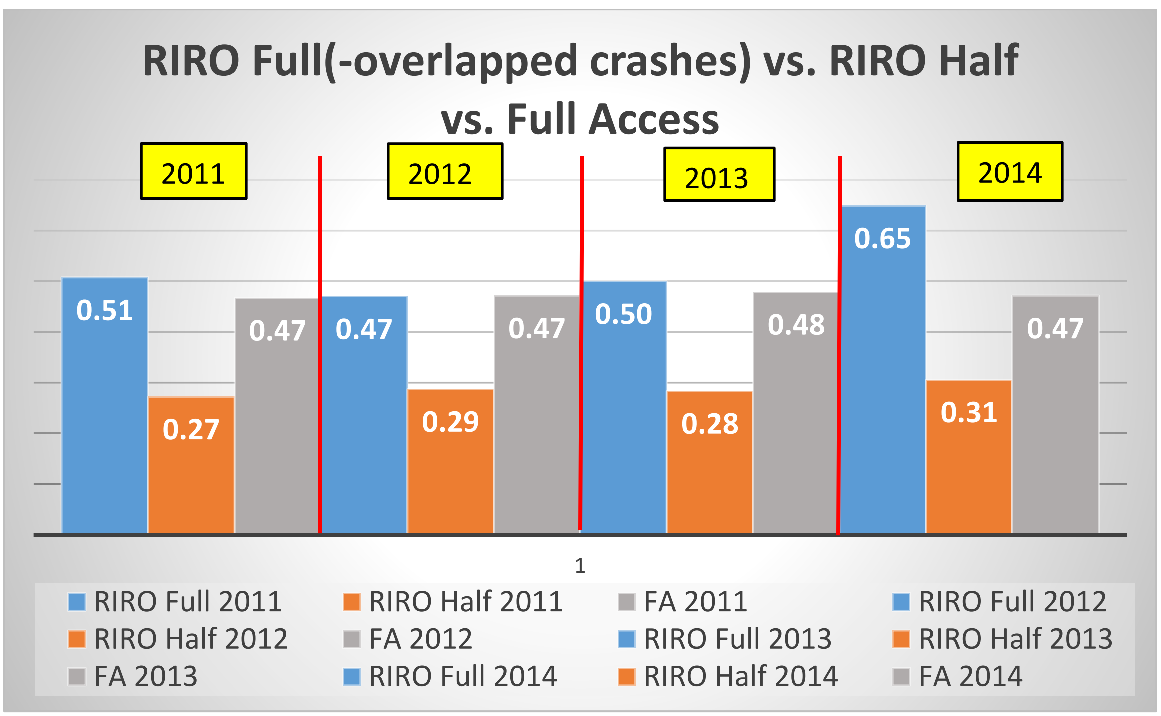

Figure 4.8: Crash Rates for Driveways after Removing Overlapped Crashes

Additionally, Table 4.2 provides a summary of four years of crash data for the 11 corridors in SC, that were initially selected based on their high 4-year average crashes. The two primary classes of driveways analyzed are: 1) without median treatment, and 2) with median treatment. Median treatments may include raised, grassed, or some type of longitudinal delineator. Table 8 shows that there is significant disparity between the 4-year crash rate for RIRO driveways without median treatments (1.27) versus driveways with median treatments (0.57).

TABLE 4.2 Summary of Right-In, Right-Out Crashes

Type of Driveway	Crashes (2011-2014)	Driveways	4-year Crash Rate	Average Annual Crash Rate
RIRO without median	186	147	1.27	0.32
RIRO with median	691	1218	0.57	0.14
Total RIRO	877	1365	0.64	0.16
Full Access	12396	7221	1.72	0.43

4.5. Statistical Analysis of RIRO Driveway Crash Data

While RIRO driveway crash rate summary statistics provide insights into the crash experience of each driveway, crash rates can be deceiving in some occasions due to confounding effects of other driveway characteristics and biases towards small denominators. To address this concern, models were developed to predict the individual contribution of the RIRO characteristics of a driveway to crash incidence and determine the statistical significance of this contribution.

Incidence of vehicle crashes are random, discrete and non-negative. Two of the commonly-used statistical models used to study traffic crashes are Poisson and Negative Binomial regression models. A major reason for frequent usage of these models is their ability to effectively identify a broad range of risk factors for crashes and thereby provide valuable information for users to select mitigation measures. As the mean and variance of crashes per driveway are not approximately equal, Poisson model was deemed inappropriate for this study. For this study, Negative Binomial Regression model was employed to identify driveway geometrics and roadway characteristics that affect driveway related crashes.

The negative binomial model is shown in the equation below:

$$\ln \lambda_i = \beta X_i + \varepsilon_i$$

where:

- λ_i is the expected number of crashes for driveway *i*,
- X_i is a vector of explanatory variables,
- β is vector of estimable coefficients, and

- $\exp(\varepsilon_i)$ is a gamma-distributed error term with mean one and variance α

A negative binomial regression analysis was performed on the data from 3774 driveways and 2012 crash data from 6 corridors, which were selected from the initial 11 corridors included in the driveway database because of differences in geocoding crash locations by some jurisdictions compared to others. The crash data from the selected six corridors are predominantly geocoded with SCDOT's new mapped based reporting system which has been shown to be much more accurate than the previous system *(22)*. Negative Binomial Regression models were developed using R-Programming Language (in R 3.3.3).

The model takes input attribute data from comma-separated-value files, exported from Excel spreadsheets. The primary input attributes for Negative Binomial Regression include driveway width, driveway type (full access or RIRO), driveway class (low, medium, high or major turnover driveway), Driveway control (signalized or unsignalized) and Average Annual Daily Traffic (AADT) as shown in Table 4.3.

In addition to the above attributes, the RIRO variable where the value of 1 indicates it is a RIRO driveway and a value of 0 indicates it is a full-access driveway.

Table 4.3 Driveway Attributes and Input Codes

Attribute	Attribute Code	Inputs	Input Code
Segment Number	Segment_No	Number	
Driveway Number	Driveway_N	Number	
Segment Driveway Number	Seg_Dr_No	Number	
Driveway Spacing	D_Spacing	Distance (FT) - Round to nearest foot	
Driveway Turning Radius	D_Radius	Radius (FT) - Estimate	
Driveway Width	D_Width	Width (FT)	
Number of entry lanes	N_Entry_Ln	Number	
Number of exiting Lanes	N_Exit_Ln	Number	
Driveway Angle	D_Angle	Ortho	1
		Skewed	2

Driveway Corner Clearance	D_Corner_C	Distance (FT)	
Driveway Throat Length	D_Throat	Distance (FT)	
Sight Distance	Sight_Dist	Good	1
		Questionable	2
		Bad	3
Driveway Description	D_Type	Right in right out- channalized (painted- obvious geometry or raised)	1
		Right in right out- unchannalized (No left turn sign)	2
		No restriction	3
		Open driveway (too wide)	4
		Oneway	5
Auxiliary Lane from road into the driveway	Aux_Lane_R	None	1
		Left	2
		Right	3

		Both	4
Median Type On Roadway	Median_Ty	Single or double solid yellow line/no median/undivided	1
		Raised median (Including aux lane)	2
		Grass Median	3
		Two way left turn lane (TWLTL)	4
		Painted Double Double Yellow Median	5
		Median opening	6
		Aux Left Turn Lane (Bad)	7
Parking Type On Roadway	Parking_Ty	None	1
		Parallel	2
		Angle	3
		Perpendicular	4
Driveway Land Use	D_Use	Commercial	1

		Industrial_Institutional	2
		Residential	3
		Mixed Use	4
		Vacant Developed	5
		Vacant Undeveloped	6
		Other	7
Driveway Class based on volume	D_Class	Low (Single Dwelling Units)	1
		Medium Residential (Sub-Division/Apartments)	2
		Medium (Low turnover small business)	3
		High (fast food, gas station, drivethrough banks…)	4
		Major (Big box)	5
Size of Land Use	D_Use_Size	Low: 0-10 Parking	1
		Medium: 11-50 Parking	2

		Large: >50 Parking	3
		Extra Large: Big box, Mall, High Rise, Parking Block	4
Driveway Use Shared?	Sh_Use	Yes	1
		No	2
Number of Driveways per Use	No_D_Use	One of One	1
		One of Two	2
		One of Many	3
Driveway Hierarchy	D_Hierarch	Primary Drive	1
		Secondary Drive	2
		Not Applicable	3
Control at Driveway	D_Control	Unsignalized	1
		Signalized	2
Any additional comments	Comments		
Data Collector	Student	Name of Student	Text

Right In-Right Out Class	RIRO_Class	Painted Island Good	1
		Painted Island Bad	2
		Raised Island Good	3
		Raised Island Bad	4
		Raised/ Grass Median	5
		Painted (Double Double) Median	6
		Combination	7
		Questionable	8
		Wrong	9

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1. Negative Binomial Model Results

Negative Binomial Models were implemented for the following cases using Full and Half Buffer Overlays:

1. Full access driveways vs. all RIRO driveways (Half Buffers for RIRO)
2. Full access driveways vs. RIRO with raised median (Half Buffers for RIRO)
3. Full access driveways vs. RIRO without raised median (Half Buffers for RIRO)
4. Full access driveways vs. all RIRO driveways (Full Buffers for RIRO)
5. Full access driveways vs. RIRO with raised median (Full Buffers for RIRO)
6. Full access driveways vs. RIRO without raised median (Full Buffers for RIRO)

Table 5.1 shows the crash modification factors obtained for full and half buffer overlays and for full access vs. different types of RIRO driveways.

Table 5.1 Negative Binomial Estimation Results – Summary

CMF /Buffer type	Half Buffer	Full Buffer
FA vs. All RIRO	0.382	0.689
FA vs. Raised RIRO	0.335	0.665
FA vs. Non-Raised RIRO	0.489	0.748

Full access driveways vs. all RIRO driveways

The negative binomial estimation results of annual crashes per driveway are shown in Table 5.2, which includes a total of 189 RIRO driveways. *For this model, all RIRO driveways were assigned a value of 1 and all full access driveways were assigned a value of 0.* The results were obtained for Full and Half Buffer overlays for average crashes for the years 2011 to 2014.

Table 5.2 Negative Binomial Estimation Results – Half Buffers (All RIROs)

Variables	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	-17.301760	0.832649	-20.78	< 2e-16
D_Width	0.020971	0.001506	13.93	< 2e-16
D_Class4	0.775981	0.066337	11.70	< 2e-16
D_Class5	0.987578	0.095001	10.39	< 2e-16
D_Control	1.199351	0.103232	11.62	< 2e-16
LN(AADT)	1.560474	0.082372	18.94	< 2e-16
RIROorFA	-0.963053	0.126720	-7.60	2.97e-14

Table 5.3 Negative Binomial Estimation Results – Full Buffers (All RIROs)

Variables	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	-17.473587	0.826440	-21.14	< 2e-16
D_Width	0.021119	0.001462	14.45	< 2e-16
D_Class4	0.775194	0.065043	11.92	< 2e-16
D_Class5	0.985066	0.092477	10.65	< 2e-16
D_Control	1.145503	0.101456	11.29	< 2e-16
LN(AADT)	1.577820	0.081728	19.31	< 2e-16
RIROorFA	-0.372851	0.100764	-3.70	0.000215

The first column in Table 5.2 shows the final model variables; they were obtained through a systematic evaluation and removal of variables with little-to-no impact on model performance. Column 2 of Table 5.2 shows the estimated coefficients of variables. A positive coefficient is interpreted as increasing crashes and a negative coefficient as decreasing crashes. Column 3 shows the standard errors for the regression coefficients. The last two columns show the z-values (test statistics) and p-values for the null hypothesis that an individual predictor's regression coefficient is zero, given that the rest of the predictors are in the model.

The results in Table 5.2 indicate that converting a full access driveway into RIRO will decrease driveway related crashes. Conversely, increasing driveway width (as opposed to channeling entries/exits), increasing corridor volume (lnAADT), adding a driveway to serve a high-turnover fast food restaurant (Driveway Class 4), or being driveway that serves a major commercial development (Driveway Class 5) will increase crashes.

Further, the magnitude of the coefficients can be interpreted as follows. By having a RIRO driveway instead of a full-access driveway, the difference in the natural logs of expected crashes will decrease by a factor of 1.14, while holding the other variables in the model constant. Regarding the constant (intercept), it indicates that the expected number of crashes is zero (actual value for λ_i is 3.061e-8; ln(3.061e-8) = -17.302).

Additionally, it was noted that the dispersion parameters for all the negative binomial models are greater than 0 (based on output from R as indicated in red color in Figure 5.1). The variance of a negative binomial model is a function of its mean and dispersion parameter (theta). As the dispersion parameter gets larger, the variance converges to the same value as the mean, and the negative binomial models turn to a Poisson distribution. Thus, a positive dispersion parameter with a value not significantly greater than 1 indicates that the negative binomial model is more suitable than the Poisson model for analyzing driveway crashes.

```
Coefficients:
                    Estimate Std. Error z value Pr(>|z|)    
(Intercept)       -17.606447   0.837310 -21.027  < 2e-16 ***
D_Width             0.020699   0.001488  13.913  < 2e-16 ***
D_Class4            0.768389   0.066160  11.614  < 2e-16 ***
D_Class5            0.963606   0.095692  10.070  < 2e-16 ***
D_Control_Binary    1.213074   0.105816  11.464  < 2e-16 ***
LAADT               1.592041   0.082813  19.224  < 2e-16 ***
RIROorFA           -0.408623   0.121734  -3.357 0.000789 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(3.3018) family taken to be 1)

    Null deviance: 4434.6  on 3694  degrees of freedom
Residual deviance: 2915.2  on 3688  degrees of freedom
  (79 observations deleted due to missingness)
AIC: 5397

Number of Fisher Scoring iterations: 1


              Theta:  3.302 
          Std. Err.:  0.390 

 2 x log-likelihood:  -5380.962 
> 
```

Figure 5.1: R Output for Negative Binomial Model for Raised Medians (Full Buffer)

Full access driveways vs. RIRO with raised median

In the second negative binomial model, RIRO driveways with a raised median were assigned a value of 1 instead of all RIRO. The total number of RIRO driveways (with a raised median) considered for this were 189, alongside 3506 full access driveways. The results are depicted in Table 5.4 and Table 5.5.

Table 5.4 Negative Binomial Estimation Results – Half Buffers (Raised Median)

Variables	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	-17.442200	0.841172	-20.736	< 2e-16
D_Width	0.020723	0.001535	13.498	< 2e-16
D_Class4	0.768380	0.067287	11.419	< 2e-16
D_Class5	0.988337	0.097133	10.175	< 2e-16
D_Control	1.227463	0.106881	11.484	< 2e-16
LN(AADT)	1.575054	0.083218	18.927	< 2e-16
RIROorFA	-1.094345	0.160757	-6.807	9.93e-12

Table 5.5 Negative Binomial Estimation Results – Full Buffers (Raised Median)

Variables	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	-17.606447	0.837310	-21.027	< 2e-16
D_Width	0.020699	0.001488	13.913	< 2e-16
D_Class4	0.768389	0.066160	11.614	< 2e-16
D_Class5	0.963606	0.095692	10.070	< 2e-16
D_Control	1.213074	0.105816	11.464	< 2e-16

LN(AADT)	1.592041	0.082813	19.224	< 2e-16
RIROorFA	-0.408623	0.121734	-3.357	0.000789

Full access driveways vs. RIRO without raised median

Table 5.6 and Table 5.7 show the results of performing a negative binomial regression model between FA driveways and RIRO Driveways without raised median (number of RIRO driveways without median treatment =79)

Table 5.6 Negative Binomial Estimation Results – Half Buffers(Non-Raised Median)

Variables	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	-17.298466	0.838505	-20.630	< 2e-16
D_Width	0.022368	0.001652	13.536	< 2e-16
D_Class4	0.744585	0.068042	10.943	< 2e-16
D_Class5	0.986169	0.097111	10.155	< 2e-16
D_Control	1.177896	0.105788	11.135	< 2e-16
LN(AADT)	1.557018	0.082949	18.771	< 2e-16
RIROorFA	-0.715166	0.201297	-3.553	0.000381

Table 5.7 Negative Binomial Estimation Results – Full Buffers (Non-Raised Median)

Variables	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	-17.313607	0.834870	-20.738	<2e-16
D_Width	0.022431	0.001645	13.632	<2e-16
D_Class4	0.748174	0.067616	11.065	<2e-16
D_Class5	1.008360	0.095699	10.537	<2e-16
D_Control	1.142163	0.104858	10.893	<2e-16
LN(AADT)	1.558612	0.082580	18.874	<2e-16
RIROorFA	-0.289892	0.170964	-1.696	0.09

RIRO without raised median vs. RIRO with raised median

Table 5.8 shows the results of performing a negative binomial regression model between RIRO Driveways without median treatment and RIRO driveways with raised median treatment (number of RIRO driveways without median treatment = 79, number of RIRO driveways with a median treatment = 189). The results in Table 5.8 represent full buffer overlay analysis of crashes. It can be observed that by using a more conservative approach i.e. full buffers, there was a negative correlation between RIRO aspect of the driveway and the crashes. This indicates a reduction in crashes by converting RIRO driveways without a median treatment to RIRO driveways with a median treatment.

Table 5.8 Negative Binomial Estimation Results (RIROs)

Variables	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	-19.300091	3.912754	-4.933	8.11e-07
D_Width	0.013016	0.003601	3.615	0.00030
D_Class4	1.199506	0.198111	6.055	1.41e-09
D_Class5	0.783013	0.266166	2.942	0.00326
D_Control	0.070152	0.313737	0.224	0.82307
Ln(AADT)	1.761145	0.383178	4.596	4.30e-06
RIROorFA	-0.294221	0.194070	-1.516	0.12950

5.2. Development of Crash Modification Factors

Crash modification factors (CMFs) capture the relationship between a change in a specific highway or roadside design element (e.g., lane width) and safety. It is a multiplicative factor or a function used to compute the expected number of crashes after implementing a given countermeasure at a specific site. Thus, given a CMF, the expected crash frequency would be multiplied by this value prior to treatment. A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after implementation of a given countermeasure. For example, a CMF of 0.9 indicates an increased safety benefit; more specifically, a 10%

expected reduction in crashes. On the other hand, a CMF of 1.1 indicates an expected degradation in safety; more specifically, a 10% expected increase in crashes.

Based on the coefficients calculated in the negative binomial model, this study estimates the CMFs for RIRO driveways. This approach of estimating CMFs assumes that each model variable is independent, and therefore not influenced by the value of any other variable. Another assumption of this approach is that the relationship between the change in variable value and change in crash frequency is exponential, as indicated by the negative binomial model (unless the independent variable is a logarithm, which leads to a Power Law).

CMFs for the negative binomial models of the six scenarios (Full and Half Buffers for the average crashes for the years 2011 to 2014) are as follows:

1. Full access driveways vs. all RIRO driveways (Half Buffer): CMF = 0.382
2. Full access driveways vs. RIRO with raised median (Half Buffer): CMF = 0.335
3. Full access driveways vs. RIRO without raised median (Half Buffer): CMF = 0.489
4. Full access driveways vs. all RIRO driveways (Full Buffer): CMF = 0.689
5. Full access driveways vs. RIRO with raised median (Half Buffer): CMF = 0.665
6. Full access driveways vs. RIRO without raised median (Half Buffer): CMF = 0.748

The CMF for Half Buffers of RIRO driveways with a physical median based on the crash data from 6 corridors in South Carolina is 0.335. This indicates that converting a full access driveway to a RIRO with a physical median can decrease the driveway crashes by over 66%. The CMF increases to 0.382 when all RIRO driveways are included (even those without a physical median. Based on the manner of collision as indicated in the crash report, this increase is most likely attributable to driver noncompliance.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Findings from this research confirm results from previous studies showing that RIRO driveways produce much lower crash rates than full-access driveways. However, the effectiveness of RIRO driveways is greatly dependent on driver compliance with turn restrictions. Specific findings are summarized for each of the following research concentrations:

1) Compliance data comparison for before and after bollard case study,

2) Crash rate comparison for RIRO driveways with and without median restrictions, and

3) Estimation of RIRO crash modification factors

The before and after case study conducted as part of this research showed that even a well-design RIRO driveway, meeting all published design criteria, can experience a considerable amount of illegal movements (11-15 percent of total driveway volume). The installation of longitudinal bollards resulted in immediate compliance improvement at the RIRO driveway. Additionally, the after-volume data indicated that the secondary full access driveway received increased use after installation of the longitudinal bollards, with no noticeable drop off in inbound and outbound traffic volumes indicating that the bollards exhibited no adverse impacts on business patronage.

The summary statistics of 877 crashes at 1,365 RIRO driveways along 11 major business corridors in South Carolina indicates that crash rates for RIRO driveways without a physically prohibiting median treatment (1.27, 4-yr crash rate) are more than double that of RIRO driveways with treatments (0.57, 4-yr. crash rate). Additionally, a much higher proportion of angle crashes occur at RIRO driveways without treatments, even though left-turn crossing movements should not occur, if driver compliance was not an issue.

Using driveway influence areas of RIRO driveways extending to the centreline (half buffer) and all the travel lanes (full buffer) separately, crash modification factors were calculated using statistical analysis of RIRO driveways. The reason for using full buffer overlays is that they are less conservative in terms of crash counts compared to half buffers.

Based on half buffer overlays, the results indicate that for RIRO driveways with physical median treatments (189 RIRO driveways) can reduce crashes by 67 percent as compared with full access driveways. The overall beneficial impact drops to 51 percent when RIRO driveways without physical medians (79 RIRO driveways) are combined in the analysis. Using full buffer overlays, RIRO driveways with physical median treatments (189 RIRO driveways) had 33.5 percent lower crashes compared to full access driveways. The overall beneficial impact drops to 25 percent when RIRO driveways without physical medians (79 RIRO driveways) are combined in the analysis. This can be attributed to compliance issues associated with the RIRO driveways without physical medians. The beneficial impact reduction would likely be even more dramatic if the proportion of RIRO driveways without physical medians was not small compared to RIRO driveways with physical medians.

The research has found a significant difference in terms of` safety between RIRO driveways with raised medians and those without raised medians. Therefore, there are safety benefits associated with RIROs with physical restriction for left turns. However, retrofitting raised medians is not always feasible in urban and suburban corridors due to roadway cross-sectional width limitations and construction issues. In such cases providing flexible delineation devices is both economical and time saving, yet it is also effective in providing physical restriction for illegal turn movements at the driveway.

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